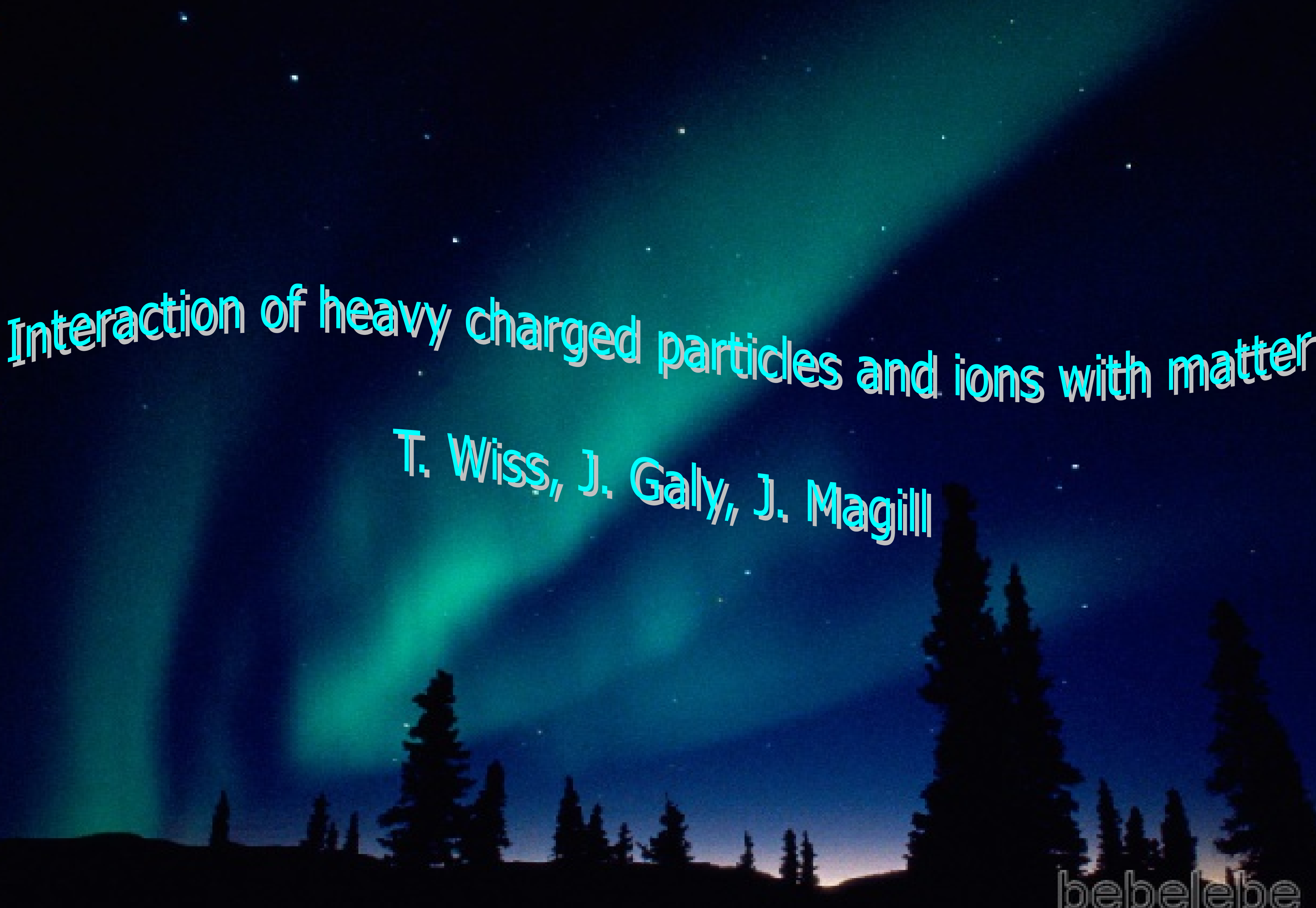

Interaction of heavy charged particles and ions with matter
T. Wiss, J. Galy, J. Magill
bebelebe

Content of the lecture

Introduction

Particle/ion-atom interactions

- basic processes on energy loss
- stopping power, range

Implementation in Nucleonica™

Examples

Origin and use of particles

Particles

e^-
n
p^+
d^+
α
heavy ions

Origin

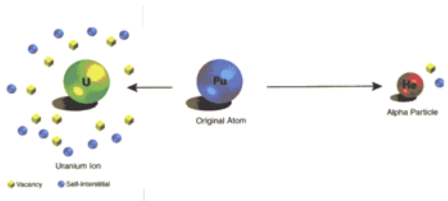
Cosmic rays
Radioactivity
- natural
- artificial

Accelerators

Use

medicine
industry
research
radioprotection

Range of different particles



	Energy, keV	Range, µm	dE/dx, Nucl./Elec.	Defects formed
Light FPs	95000	9	0.03/0.97	40000
Heavy FPs	67000	7	0.06/0.94	60000
α-particles	5000	12	0.01/0.99	200
Recoil nucleus	95	0.02	0.90/0.10	1500
Cosmic rays (p^+)	10^{17} 10^6 (typical)	Light years !		

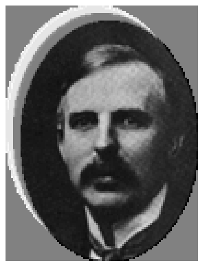
Some pioneers...

"Les rayons alpha sont des projectiles matériels susceptibles de perdre de leur vitesse en traversant la matière" (1900)

H. Becquerel

P. Curie

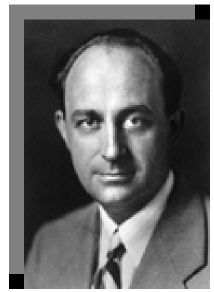
M. Curie-Slodowska



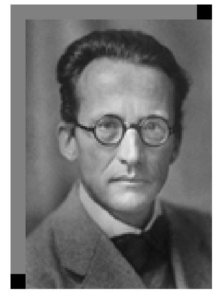
E. Rutherford

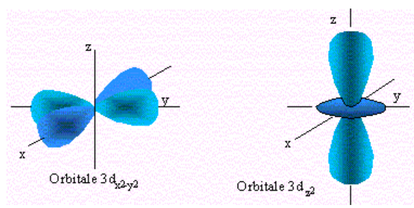
N. Bohr

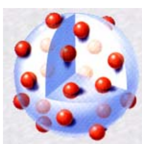
E. Fermi

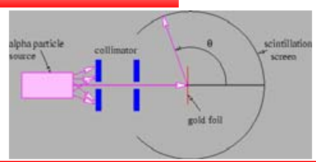


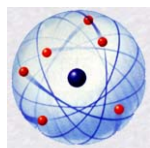
E. Schrödinger

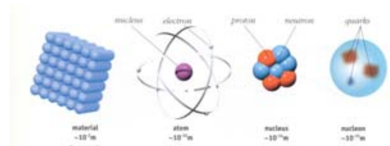












1896 — 1911 — today….

Particle/ion-matter interactions

Slowing down of a particle/ion in a target

- history of the particle
  energy loss of a particle, *range*, interactions

- history of the target atoms
  displacements, recombinations, ionization, excitation, radiation damage build-up

Areas of interest

Nuclear industry, nuclear medicine, space applications, semi-conductor, geology…

Interaction of a charged particle with matter

Inelastic collisions with an electron

main process of energy loss producing excitation and ionization

Inelastic collisions with a nucleus

Bremsstrahlung and coulombic excitation

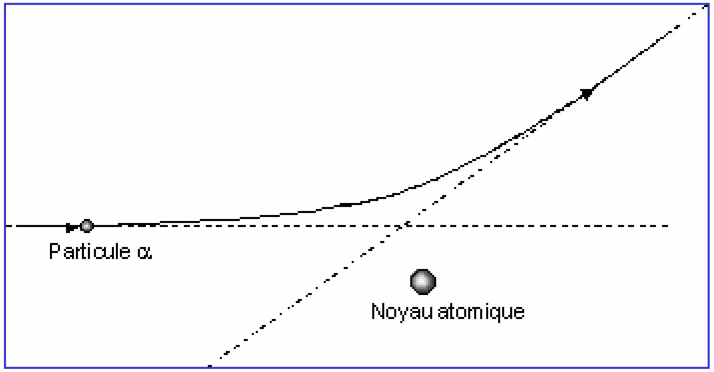
Elastic collisions with a nucleus

Rutherford diffusion

Elastic collisions with an electron

Rutherford diffusion

$$\frac{1}{2}M_1 v_1^2 = \frac{1}{4\pi\varepsilon_0}\frac{Z_1 Z_2 e^2}{D}$$



D was measured by Rutherford.

The minimum D value indicated the upper limit of the nuclei radius.

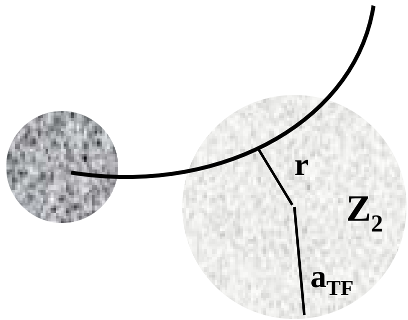
- Many interactions are needed to stop the particle (low probability of energy transfer).

- the probability to transfer energy is inverse to the mass of the target particle (mainly electrons will participate).

- Probability higher at low velocity (end of range).

Definitions

....In fact..



Screening of e⁻ : Thomas-Fermi potential

$$V(r) = \Phi\left(\frac{r}{a_L}\right)\frac{Z_1 Z_2 e^2}{r}$$

with the screening length (Lindhard)

$$a_L = \frac{0.8853}{\left(Z_1^{2/3} Z_2^{2/3}\right)^{1/2}} a_0$$

Interatomic potential

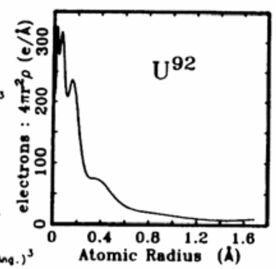
Other description of the screening functio
by Lenz, Jensen, Sommerfeld, Moliere

Inter-penetration of the electron clouds
Hartree-Fock-Slater calculations
However, good approximation by TF

Charge distribution in single atom

U^{92}

Atomic Number 92
Atomic Weight .... 238 amu
Mass Density .... 19 g/cm^3
Atomic Density .... 0.0482 Atoms/Ang.^{3}
Lattice Type .... ORC
Lattice Constant .... 2.85 Ang.
2nd Lattice Constant... 1.88 Ang.
Muffin-Tin Radius ...... 1.45 Ang.
Fermi Velocity-Theory (Cont).. 1.03 Vo
Fermi Velocity-Theory (Disc).. 1.01 Vo
Fermi Velocity-Experiment..... None Avail.
Interstititol Volume... 7.99 (Ang.)^3
Interstititol Charge... 1.89 electrons
Interstititol Density (Disc) .. 0.238 e/(Ang.)^3



Rad. (A)	Chg. (e/A^3)	Rad. (A)	Chg. (e/A^3)	Rad. (A)	Chg. (e/A^3)	Rad. (A)	Chg. (e/A^3)
0.00104	2.65E6	0.0477	9.82E3	0.255	122	1.32	0.342
0.00207	1.85E6	0.0519	8.57E3	0.272	93.3	1.45	0.246
0.00311	1.30E6	0.056	7.62E3	0.288	75.8	1.46	0.246
0.00415	9.12E5	0.0601	6.82E3	0.305	64.5	1.47	0.246
0.00519	6.47E5	0.0643	6.07E3	0.355	46.8	1.49	0.246
0.00622	4.64E5	0.0684	5.37E3	0.388	38.1	1.5	0.246
0.00726	3.40E5	0.0726	4.70E3	0.421	30	1.51	0.246
0.0083	2.54E5	0.0809	3.52E3	0.454	23	1.52	0.246
0.00933	1.98E5	0.0892	2.60E3	0.487	17.3	1.54	0.246
0.0104	1.56E5	0.0975	1.95E3	0.521	12.9	1.55	0.246
0.0124	1.10E5	0.106	1.53E3	0.554	9.68	1.56	0.246
0.0145	8.62E4	0.114	1.27E3	0.587	7.41	1.57	0.246
0.0166	7.27E4	0.122	1.11E3	0.62	5.83	1.59	0.246
0.0187	6.31E4	0.131	1.01E3	0.653	4.72	1.6	0.246
0.0207	5.51E4	0.139	9.25E2	0.72	3.33	1.61	0.246
0.0228	4.80E4	0.147	8.50E2	0.786	2.52	1.62	0.246
0.0249	4.15E4	0.156	7.75E2	0.852	1.95	1.63	0.246
0.027	3.56E4	0.172	6.17E2	0.919	1.51	1.65	0.246
0.029	3.04E4	0.189	4.65E2	0.985	1.16	1.66	0.246

Definitions

- CSDA range: the continuous slowing down approximation range is obtained by integrating the reciprocal of the total stopping power with respect to the energy.

- The projected range is the value of the depth measured along the initial direction at which a charged particle/ion will be at rest.

Range calculation in Nucleonica™

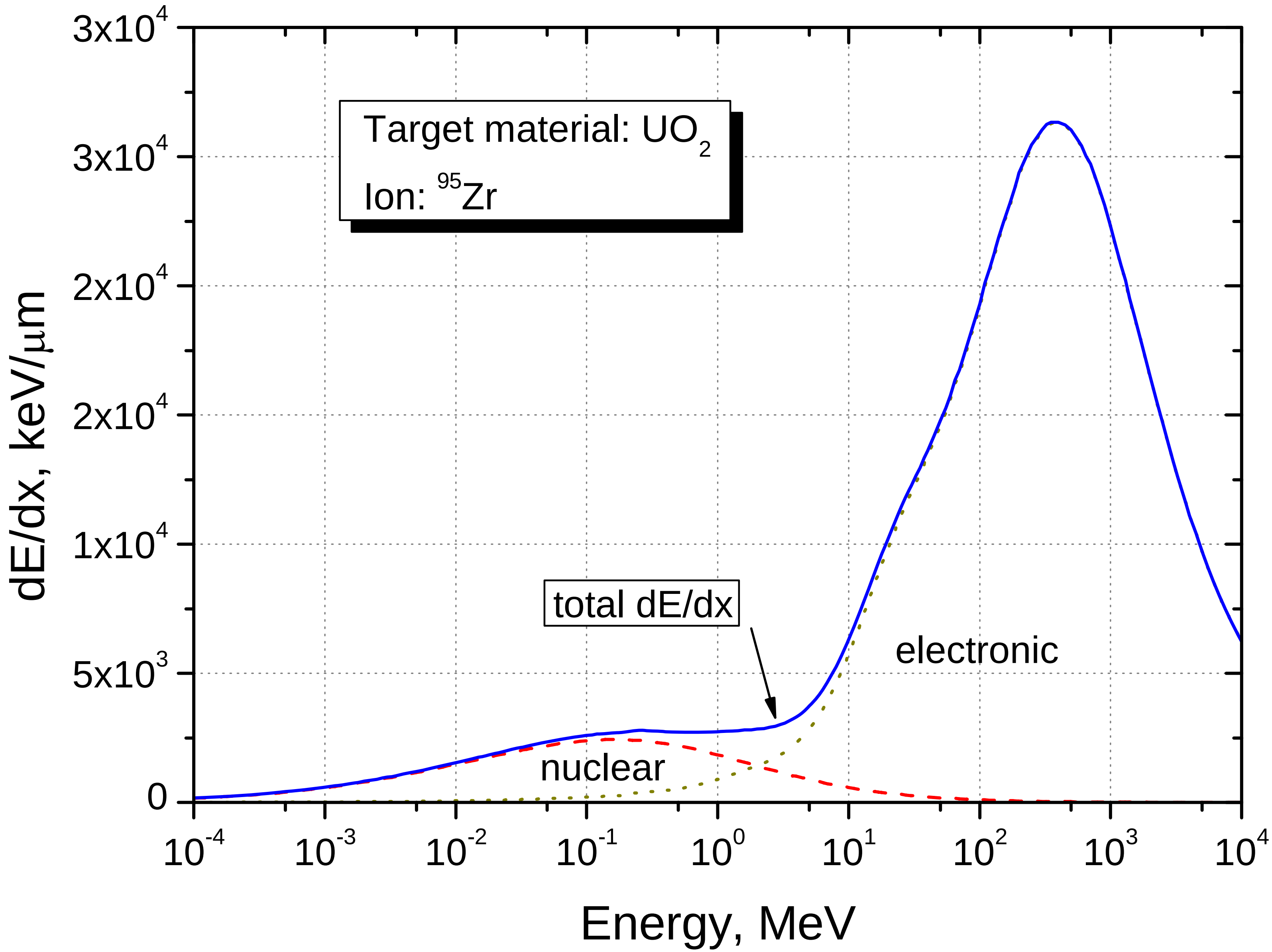
The Range program is a user friendly module for the calculations of the stopping power and range of charged particle in matter.

For ions, the SR_module from SRIM is used to calculate stopping powers and ranges for ions (with energy up to 2 GeV/amu) up to uranium with an accuracy of about 3-4% to the measured values.

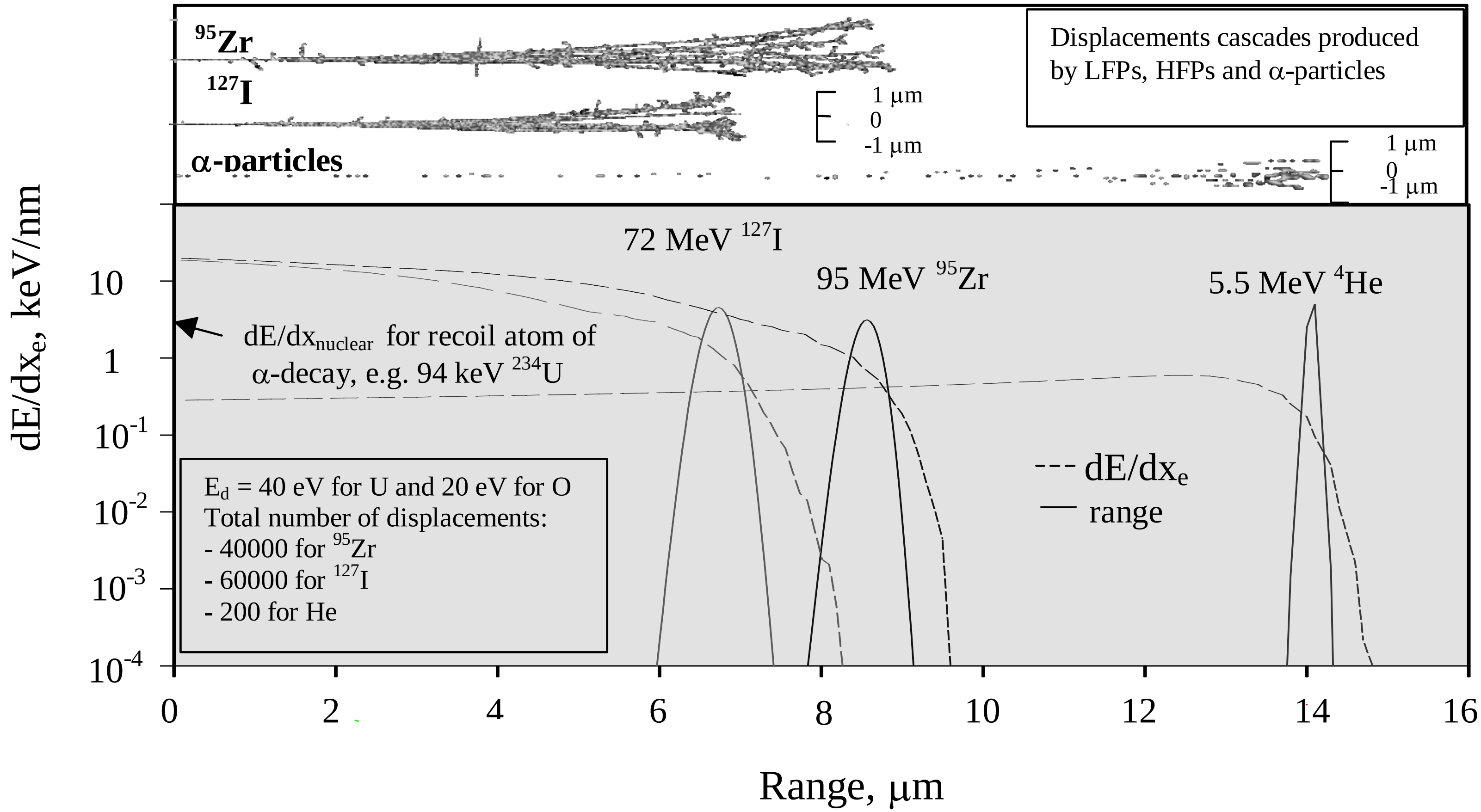
J. P. Biersack and J. F. Ziegler, "The Calculation of Ion Ranges in Solids with Analytic Solutions", 157-176, in "Ion Implantation Techniques", H. Ryssel and H. Glawischnig, Springer Verlag, Berlin (1982).

J. F. Ziegler, J. P. Biersack and U. Littmark, "The Stopping and Range of Ions in Matter", Pergamon Press , New York (1985).

Energy loss

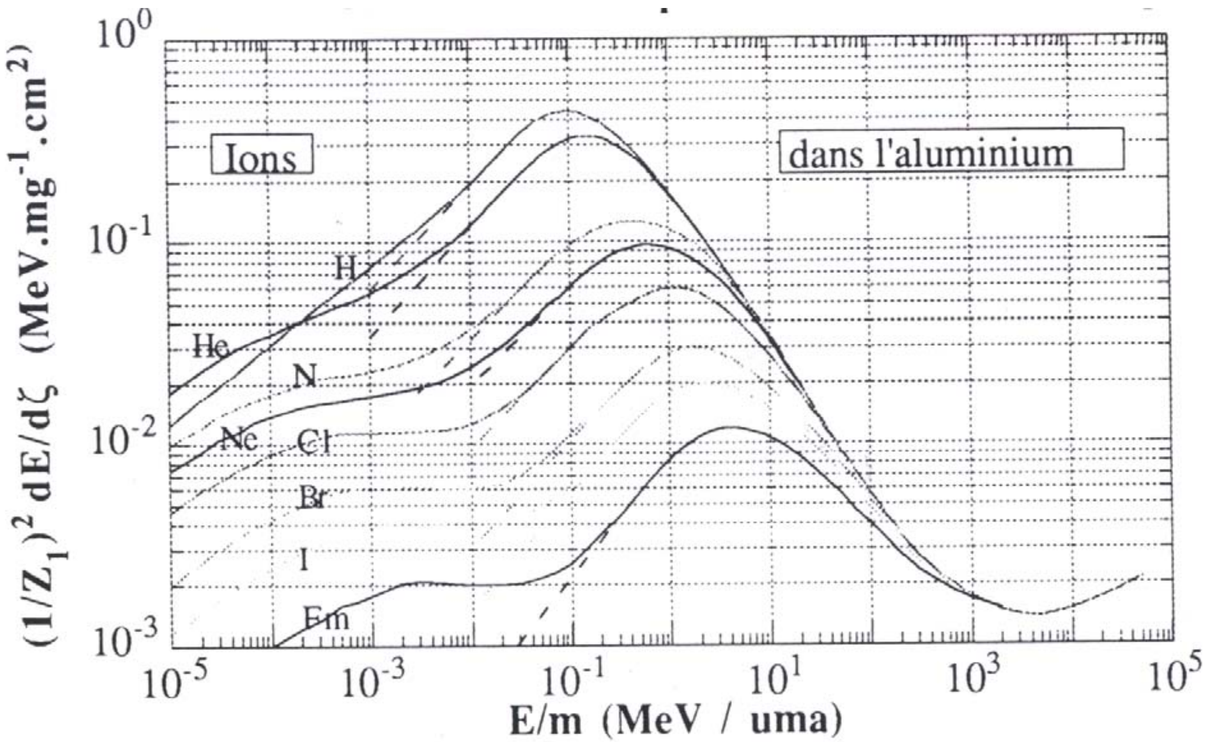

Target material: UO2
Ion: 95Zr
total dE/dx
electronic
nuclear
dE/dx, keV/μm
Energy, MeV
3x10^4
3x10^4
2x10^4
2x10^4
1x10^4
5x10^3
0
10^-4
10^-3
10^-2
10^-1
10^0
10^1
10^2
10^3
10^4

Stopping power and ranges



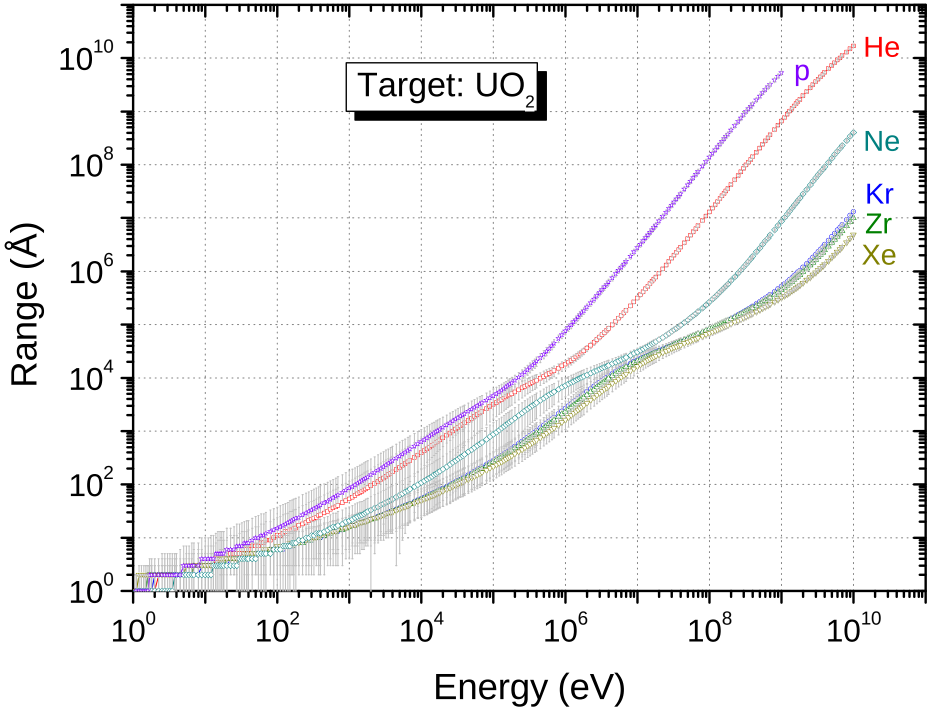
Stopping power of heavy ions

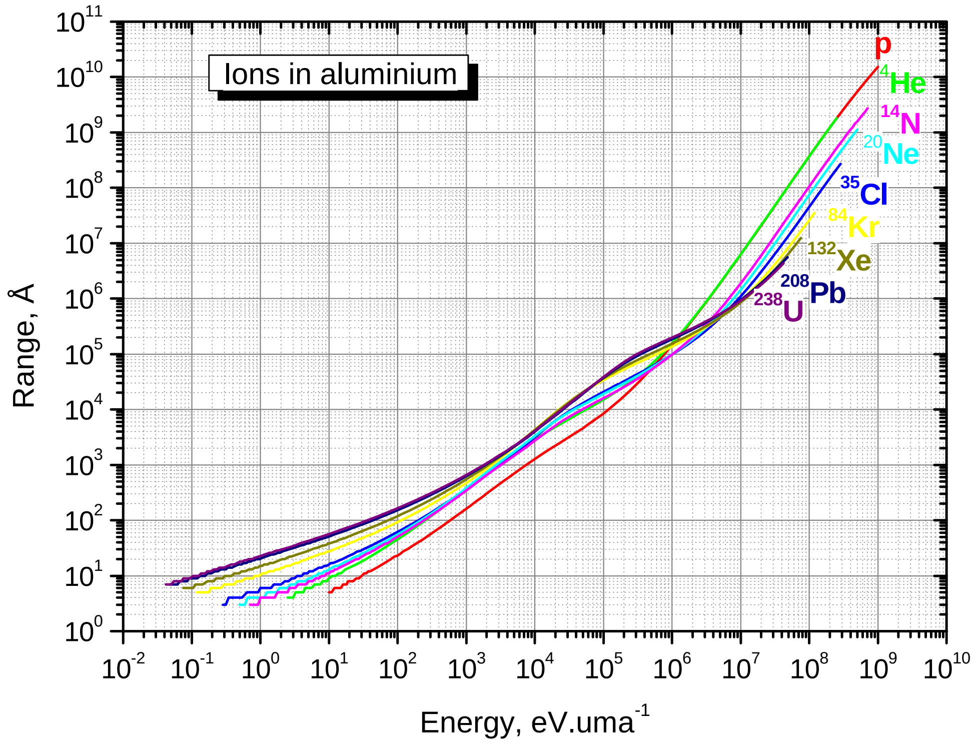
The stopping power for heavy ions can be assessed by the Bethe-Bloch approach but needs to be corrected by the effective charge (dependant on the velocity).



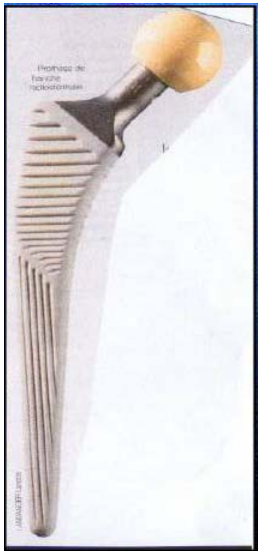
At high energy the curves of the heavy ions join the one of the proton.
From one medium to another Z/A correction.

Range of various particles/ions



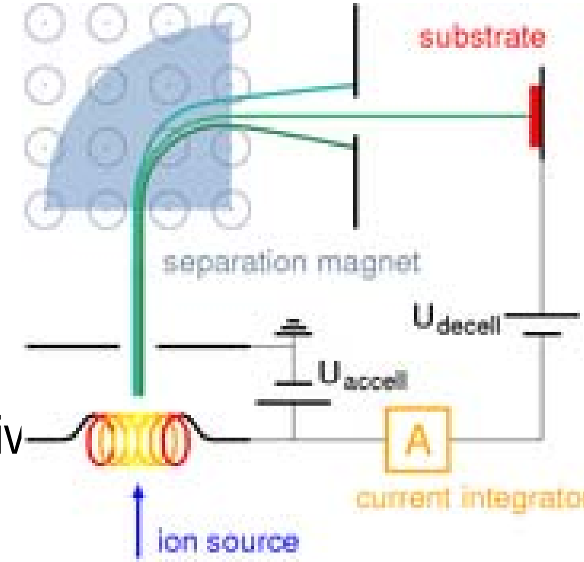


Ion implantation: applications



Physical and chemical modifications

- Compression of the irradiated surface
- Amorphisation, formation of metallic glasses.
- Creation of supersaturated solid solutions.
- Precipitation of phases into small grains.
- Formation of a passive layer.
- Modification of the surface energy/chemical reactiv
- Enhanced oxide layer formation.



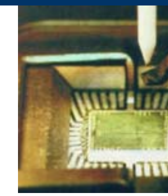
Ion implantation allows combination of many substrate and implanted species.

Materials	Applications	Implanted species	Improvement factor
Ti-6Al-4V, CoCrMo, UHMWPE	reduction of articular prostheses wear (e.g. hip)	N	x 8 to 100
Silicone	catheters thrombo-resistance	N, O, C, Ar	x 10
Silicone	antibacterial surfaces for catheters	Ag	100 % bacteria disappearance

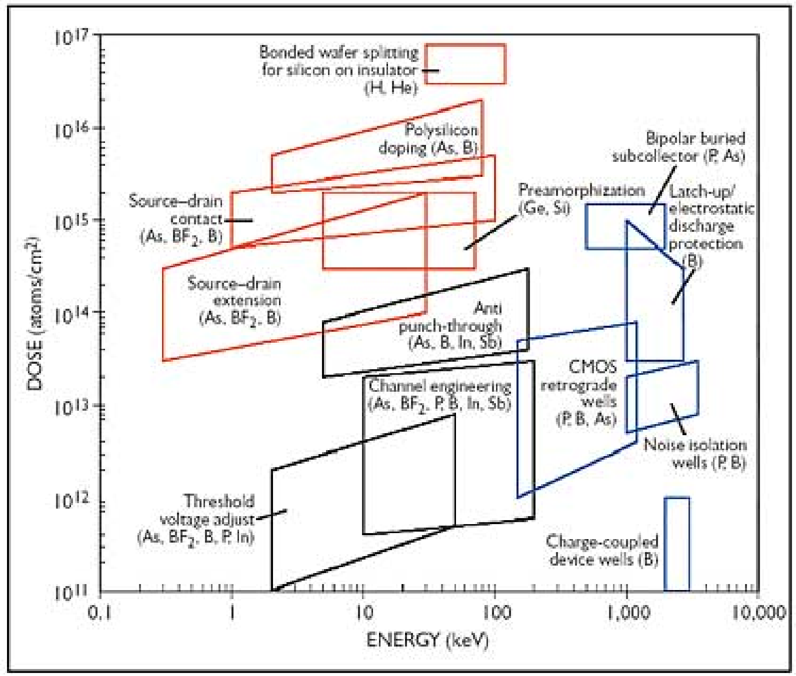
Ion implantation: applications

Properties	MECHANIC	CORROSION	PHYSICO-CHEMICAL PROPERTIES
Improvements	Wear Friction Fatigue	High T° oxidation Water corrosion Hydrogen adsorption Salt corrosion	Surface energy Adhesion Chemical activity Catalysis
Domain	Spatial Aeronautics Mechanics Tools Biomedical Instrumentation	Chemical Industry Aeronautics Engines, turbines Corrosive products Nuclear Wet and aqueous products Biomedical	Biocompatibility in general Hemo-compatibility Cyto-compatibility. Antithrombogenic action

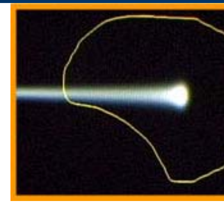
Junctions in semi-conductors



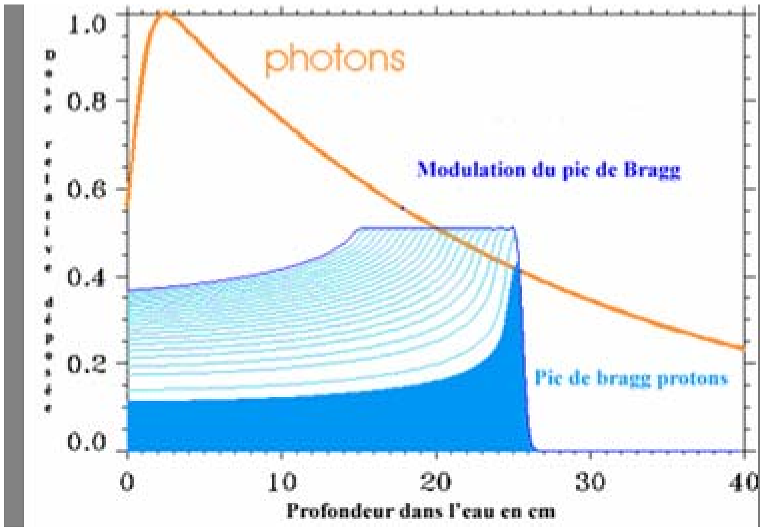
The majority of integrated circuits are fabricated from single crystal silicon wafers doped with Group III elements (B, Al, Ga, In ,Tl), p-type, or with Group V elements (N, P, As, Sb, Bi), n type. Transistors are formed by junctions between n-type and p-type silicon in the sequences n-p-n or p-n-p. Dopants are impurity elements added to the semiconductor crystal to form electrical junctions or boundaries between "n" and "p" regions in the crystal. The most common doping methods include diffusion and **ion implantation**.

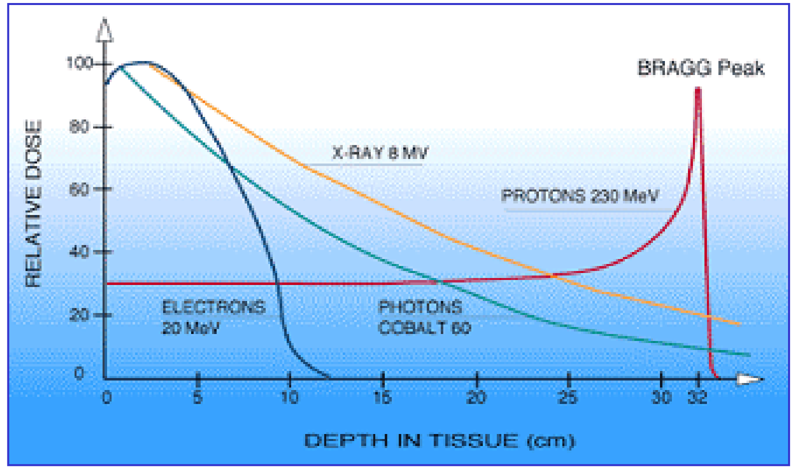


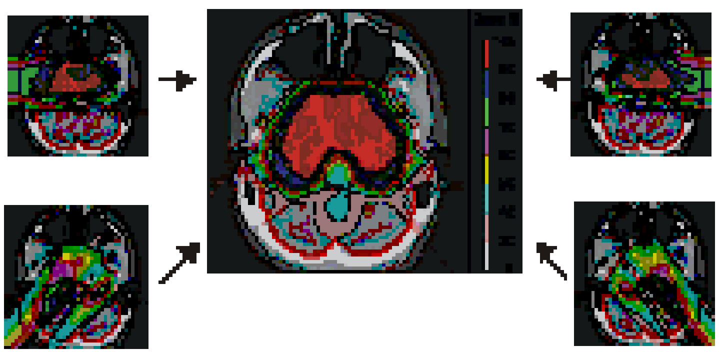
Protontherapy

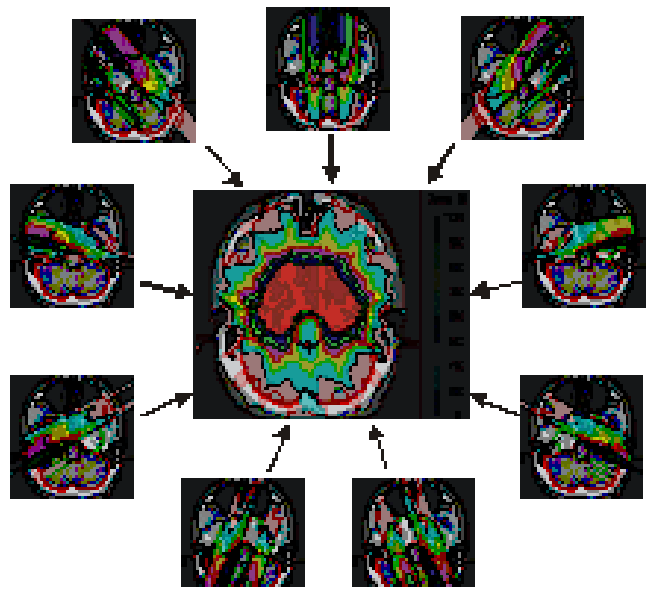


- Protontherapy (used in treatment of tumors)
  200 MeV p+ can penetrate in 22 cm tissue









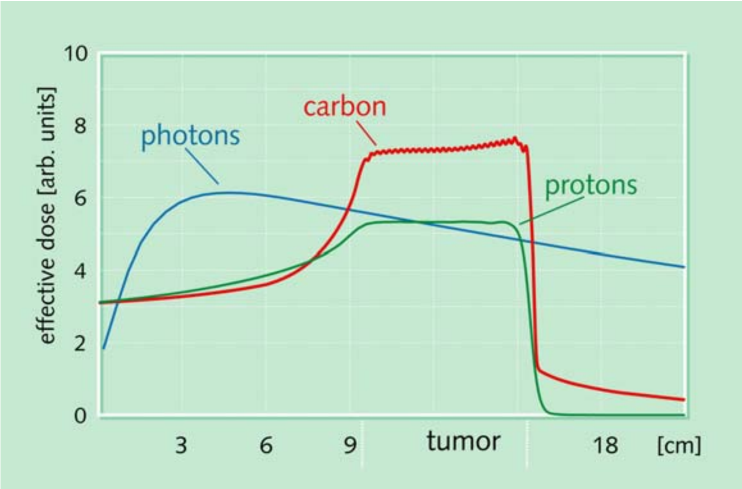
Carbon Ion Radiotherapy @

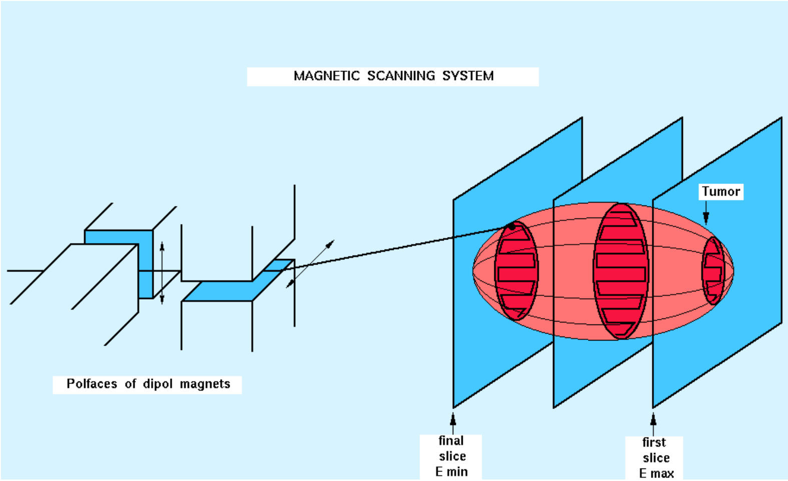
Tumour patients (head region) have been treated with accelerated carbon ions beams at GSI since the end of 1997.

- aim carbon ions directly at the tumour with great precision.

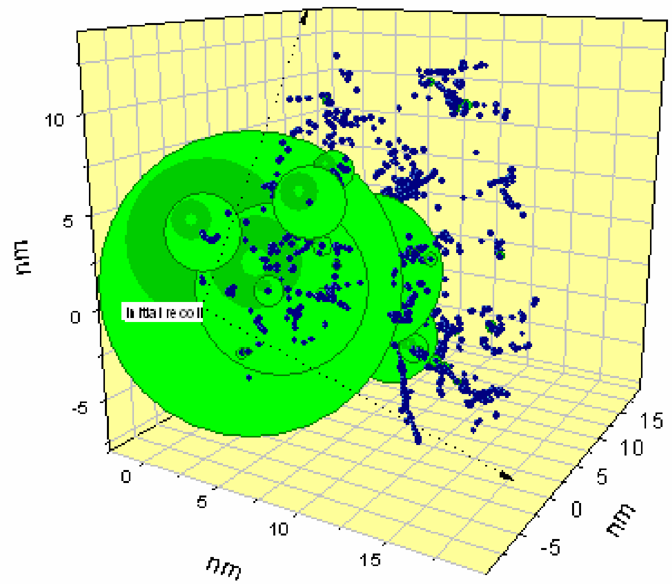
- high biological efficiency of carbon ions.

Based on the studies at GSI, a therapy centre in Heidelberg is being built where up to 1,000 patients per year could be treated.



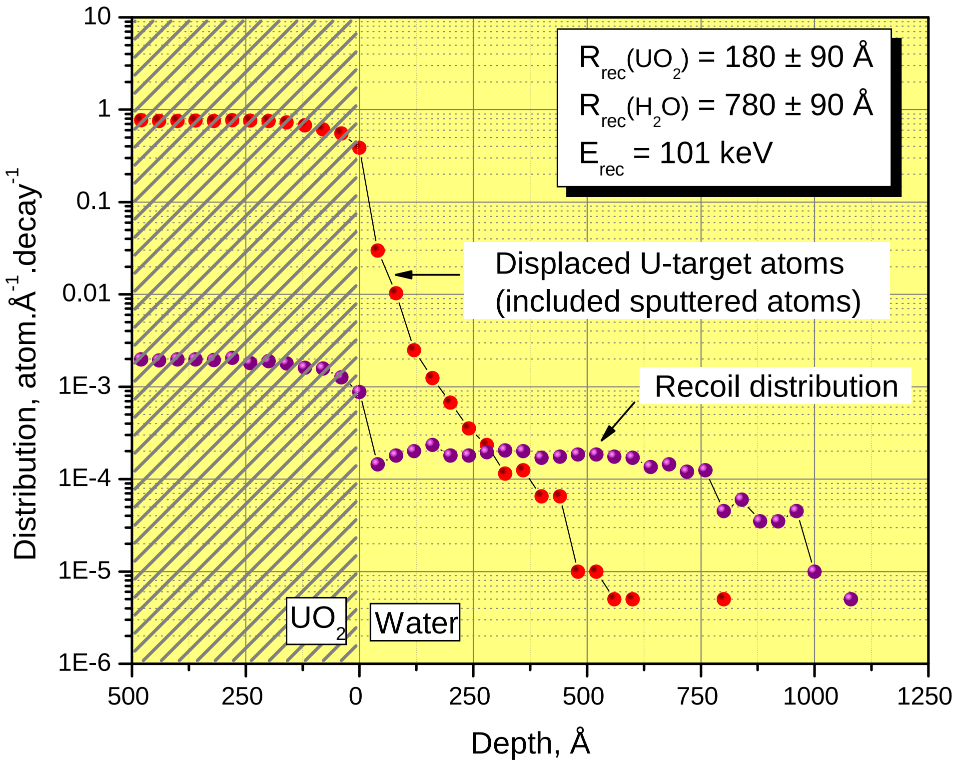


Alpha-decay: range in H_2O



Cascade from recoil

Distribution in water of the emitted recoil atoms from spent fuel surface



Radiolysis effects


AURORA BOREALIS
Marc Wächter
END...

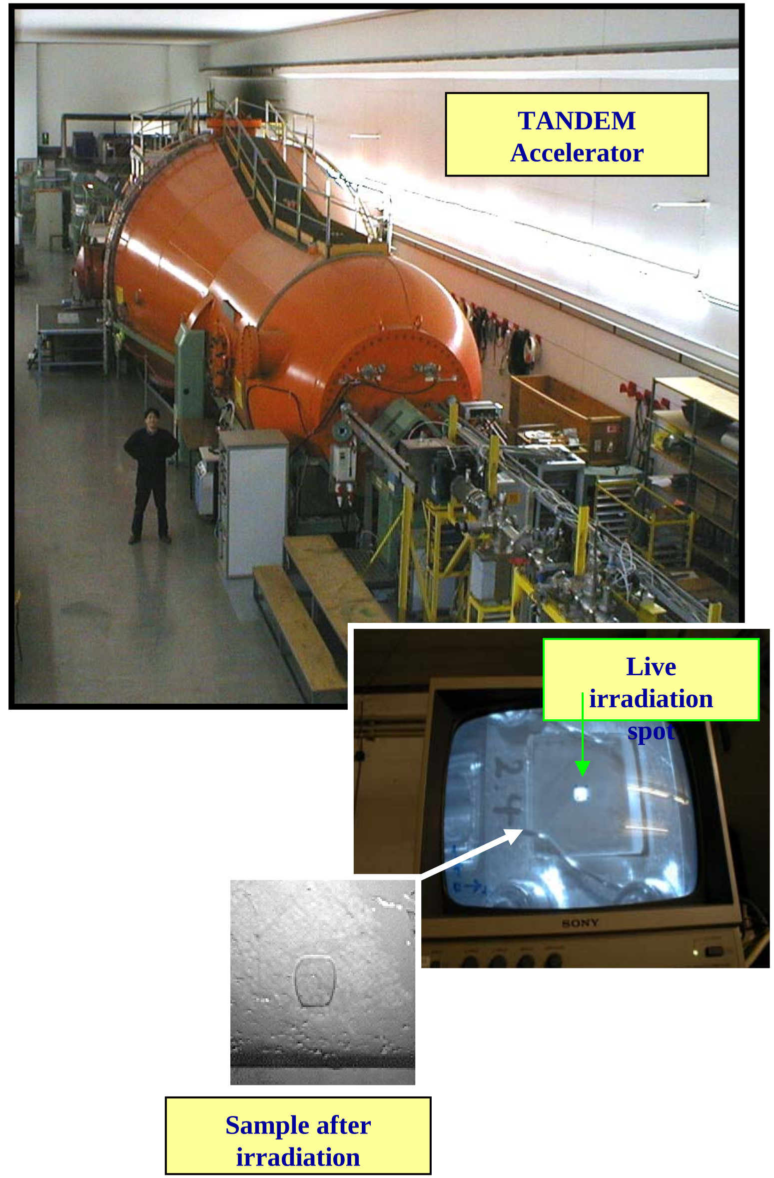
Case study

To simulate fission damage in a material candidate for transmutation of actinides, a single crystal sample (Al2O3) will be implanted with:

70 MeV iodine (heavy fission product) and 100 MeV Zr (light fission product)

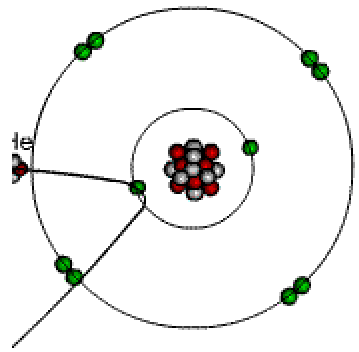
- What is the expected range of these two elements in ZrO_2 ?
- What is the stopping power at the beginning of the path (keV/µm)

(d=3.97 $g.cm^{-3}$)

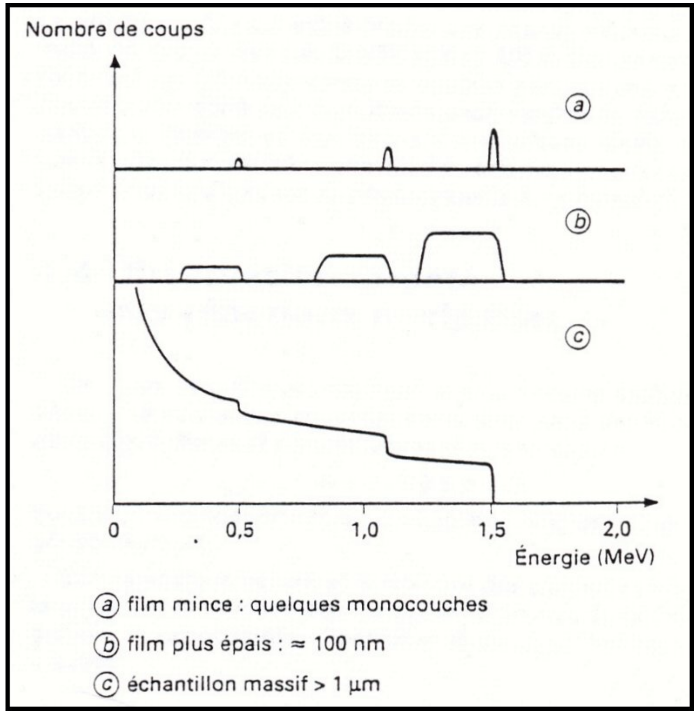


Case study: RBS

Analysis of the implanted sample with Rutherford Backscattering (RBS)



A high energy beam is directed at a sample. A detector is placed such that particles which scatter from the sample at close to a 180 degree angle will be collected. The energy of these ions will depend on their incident energy and on the mass of the sample atom which they hit.



RBS can be used as a means to perform a depth profile of the composition of a sample.

Case study

Analysis of the implanted sample with Rutherford Backscattering (RBS)

Exercise: from the two following available ions which is most appropriate to analyse the implanted Al2O3 sample i.e. to determine the implantation profile of the fission products (*the range must be sufficient for detection of backscattered ions*):

- Analysis with 2 MeV He^{2+}

- Analysis with 1 and with 2 MeV p^{+}

Case study

The following ranges have been obtained

- 70 MeV I : µm
- 100 MeV Zr : µm
- 2 MeV He^{2+} : µm
- 1 MeV p^{+} : µm
- 2 MeV p^{+} : µm

The 2 MeV p^{+} should be retained for analysis